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Climate Change and Its Potential Impacts on Insect-Plant Interactions

Somala Karthik, M.S. Sai Reddy and Gummudala Yashaswini

Abstract

The most dynamic and global environmental issue to date is climate change. The consequences of greenhouse effect and climate change from rising temperatures, frequent droughts, irregular rainfall, etc. are already evident. Insects and plants are affected by climate change and extreme weather events and the direct impact of anthropogenic climate change has been reported on every continent, in every ocean and in most major taxonomic groups. In the modern period, as a result of natural cycles and anthropogenic activities and their effects on the global climate, plants are typically susceptible to new environmental factors, *i.e.* higher levels solar radiation, rise in temperatures, greenhouse effect and changes in rainfall patterns over the seasons. Increased temperatures, CO₂ and rapid changes in rainfall patterns can dramatically alter the biochemistry of plants and thus plant defence responses. This can have important implications in insect fertility, feeding rates, survival, population size, and dispersal. The relationships between plants and insects are thus changed with significant consequences for food security and natural ecosystems. Similarly, mismatches between plants and insect pollinators are caused by the acceleration of plant phenology by warming. Human nutrition which depends on insect pollination can be affected with reduction in plant reproduction and fitness. Thus, understanding abiotic stress reactions in plants and insects is relevant and challenging in agriculture. In the preparation and implementation of effective strategies for future insect pest management programmes, the impact of climate change on crop production, mediated by changes in the populations of extreme insect pests should be carefully considered.

Keywords: Climate change, temperature, CO₂, insects, plants

1. Introduction

Climate change is a worldwide threat that is unavoidable and immediate which encompasses a combination of natural and anthropogenic changes in the environment. Worldwide attention has been attracted by recent changes in global climate phenomena and consequent losses. Climate change, according to the Intergovernmental Panel on Climate Change (IPCC), is described as “any change in climate over time, whether due to natural variability or as a result of human activity”. Human activities are responsible for much of the warming that has been observed over the last 50 years. From 1990 to 2100, the global mean surface

temperature is expected to rise by 1.4 to 5.8°C. In the next 100 years, if temperatures increase by around 2°C, the detrimental global warming effects will begin to spread in much of the world's region [1]. In addition, CO₂ levels rose from 280 ppm to 401 ppm in 2015 (Mauna Loa Observatory: Hawaii).

Insects constitute over half of the estimated 1.5 million organism species of the biodiversity identified so far on the planet and are fundamental to the structure and function of ecosystems. Insects are among the most susceptible groups of organisms to climate change as they are ectothermic, so thermal changes have strong direct effect upon their growth, reproduction and existence [2]. The effects of climate change on insect pests are of greater significance because insects are involved in many biotic interactions, such as plants, natural enemies, pollinators and other organisms, which play a major role in the ecological functioning of insect pests [3]. The impact of climate change on arthropod extinction rates is 100 to 1000 times greater than what has occurred previously, with about 45 to 275 species becoming extinct on a daily basis. An increase in a temperature rise of 6°C would result in the mass extinction of species, including humans. For example, due to hot temperatures (like heat waves) related to climate change, have resulted in a decrease in bumblebee populations by 46 per cent in North America and by 17 per cent across Europe compared to the base period of 1901 to 1974. In India Basavarajappa S, has observed a 2 per cent decline in rock bee, *Apis dorsata* colonies every year in Mysore due to increase in temperature, altering its local climate.

Climate change and extreme weather events affect insects and plants, and the direct effect of anthropogenic climate change has been recorded on every continent, in every ocean and in the majority of major taxonomic groups. In the modern era, plants are habitually vulnerable to new environmental factors *i.e.*, solar radiation, high temperatures, rise in CO₂ levels and shifts in pattern of rainfall over the seasons, as a result of natural cycles and anthropogenic activities and their impact on the global environment. Because of the close relationship between insects and host plants, through the changes undergone by their host plants, insect herbivores are likely to experience direct and indirect consequences of climate change. Global climatic changes are also expected to influence interactions between insects and plants in many ways. They may directly affect insects through changes in physiology, behaviour and life history parameters, as well as indirectly through changes in their own life history experienced by host plants.

2. Factors governing the climate change

Over thousands or millions of years, global climate change typically occurred very slowly. But today, by contrast, our environment is changing fast. There are many factors that govern the climate change around the world. The most important factors are discussed below:

2.1 The sun and the cosmic rays

Climate change is influenced by natural changes like the amount of solar energy reaching the Earth. The rate of energy emitted by the Sun varies slightly from day to day. Over many millennia the relationship between Earth and Sun can change the geographic distribution of the energy of the sun throughout the earth's surface. The orbit of Earth around the Sun is an ellipse and when it changes in shapes, the Earth moves nearer to the Sun which makes our climate much warmer. The orientation

of earth's axis can also affect the amount of sunlight reaching the earth's surface [4]. The angle of rotation of the earth's axis varies over time and it shifts from 22.1° to 24.5° and back again for around 41,000 years. With increase in the angle the summers become warmer and the winters turn colder. The Sun also emits particle radiation, primarily protons and electrons, which comprise the solar wind. These particles come near to the earth, but the earth's magnetic field averts them from reaching the surface. The earth's atmosphere reaches more intense executions, known as solar cosmic rays. Cosmic solar rays cannot be reaching the earth's surface, but are extremely energetic, collide with atoms at the top of the atmosphere, causing major magnetic field perturbations to disrupt power lines and electrical equipment [5]. It has been suggested that changes in solar output might affect our climate-both directly, by changing the rate of solar heating of the Earth and atmosphere, and indirectly, by changing cloud forming processes. The increase in absorption of solar radiation results in rise in temperatures which in turn results in upsurge of CO₂ levels. [6] suggested that rise of 1°C will result in the release of 30 petagrams of carbon from the soils, which is almost twice the amount emitted due to human activities annually.

2.2 The greenhouse effect

Greenhouse gases are the molecules that are capable of absorbing infrared radiation released from the surface of the Earth and re-radiating it back, thereby leading to the greenhouse effect phenomenon. During the history of the Earth, greenhouse gases concentrations such as water vapour, carbon dioxide, methane, nitrous oxide, ozone and certain artificial chemicals like Chloro Fluoro Carbons (CFCs) have varied considerably, and these fluctuations have triggered major climate changes at a wide range of timescales. Human activities, particularly the combustion of fossil fuels (coal, oil and natural gas), agriculture and land clearing, are responsible for rising concentrations of greenhouse gases. This has intensified the greenhouse effect, leading to earth's warming.

2.3 Human influence

The factors above mentioned affect the climate naturally. However, we could not forget the effect of human activities on the changes in climate. Early in history, influence of human on the climate would have been quite small. Since, the beginning of the Industrial Revolution, at the end of 19th Century in the atmosphere there was a rise in the emission of the amount of greenhouse gases. The number of trees being cut down by humans has also increased, resulting in reduced uptake of carbon dioxide by the forests. Black carbon (BC), a solid particle or aerosol that is not a gas, leads to atmospheric warming. Unlike GHGs, in addition to absorbing infrared radiation, BC can also directly absorb incoming and reflected sunlight. It may also settle on the snow and ice, darkening the surface and thereby increasing the snow's absorption of sunlight and accelerating the melting process. Sulphates, organic carbon, and other aerosols might cause cooling by reflecting sunlight. Clouds can interact with warming and cooling aerosols, alters a number of properties of cloud like the rate of formation, dissipation, reflectivity, and precipitation. They may contribute to cooling, by reflecting sunlight and warmth and by trapping the outgoing heat.

True insights about climate change can be provided by factors such as temperature, precipitation (amount, frequency and timing), humidity, wind (velocity, timing), gaseous concentration etc.

Factors	Insects	Plants
a. Temperature	<ul style="list-style-type: none">• Evolutionary changes• Reproductivity• Life period• Metabolism• Activity• Migration	<ul style="list-style-type: none">• Photosynthesis• Respiration• Phytochemicals• Germination• Flowering
b. Humidity	<ul style="list-style-type: none">• Development• Survival• Behaviour• Physiology• Reproduction	<ul style="list-style-type: none">• Transpiration• Nutrients from the soil• Photosynthesis• Pollination• Incidence of diseases
c. Precipitation	<ul style="list-style-type: none">• Survival• Development• Reproduction• Distribution	<ul style="list-style-type: none">• Photosynthesis• Spread of diseases• Development• Transpiration• Pollination• Competitive Suppression• Life period
d. Wind	<ul style="list-style-type: none">• Distribution• Behaviour• Abundance• Reproduction• Survival rate• Pollinating	<ul style="list-style-type: none">• Photosynthesis• Transpiration• Lodging• Chilling injuries• Pollination
e. Greenhouse gases	<ul style="list-style-type: none">• Reproductive capabilities• Distributional ranges• Physiology• Behaviour• Population dynamics	<ul style="list-style-type: none">• Photosynthesis• Stomatal conductance• Oxidative stress• Carbon to Nitrogen (C:N)

3. Effect of different climate change factors on insect pest, plants and their interactions

In agriculture, climate change can interfere in normal plant physiologies such as photosynthesis, respiration, transpiration, nutrient absorption, balance of minerals and exchange of ions etc. It may also intervene with the production of crops by altering the population and function of insect pests. Climate variables such as temperature, humidity, precipitation etc. are accountable for the growth, development and multiplication of organisms like insects, fungi, bacteria, virus etc. As with the changing climate, populations of pest are also expected to change. In addition, climate change is expected to fetch modifications in host plant resistance against insect pests. The resistance can be overcome by faster disease cycles and altered physiologies of insect pest. As global warming is caused by climate change, several insect species are affected in terms of their distribution, demography, and life history parameters. The response of an insect population to a swiftly changing

climate will be inconsistent when insects interact with different competitors, predators and parasitoids. This also affects overall food production systems that can be at critical risk due to the consequences of climate change [7]. These changes inflict consequences on human livelihood, including the rapid spread of pest and diseases of important crops. This has brought new challenges to agricultural sustainability.

3.1 Effect of temperature on insect pest and plants

The global average temperature is expected to increase by at least 4°C by the end of the 21st century, due to the increased frequency and intensity of drought and heat waves [8]. Temperature has a strong effect on insect growth, survival and reproduction and enrolls a major role in controlling the development and growth of their host plants. In addition, the development of plant secondary chemicals as well as the structural characteristics used to protect against herbivores are influenced by temperature. Thus, for both insects and plants, temperature has potentially significant consequences (**Figure 1**). Phytochemical and morphological changes in host plants are caused by changes in temperature. For example, at night temperatures of 17°C, the concentration of catecholic phenolics (chlorogenic acid and rutin) in tomatoes was significantly higher than at other temperatures [9]. Also, Rivero et al. [10] reported low polyphenol oxidase (PPO) activity of peroxidase (POX) at 35°C in tomatoes; it has been also reported that there is a substantial decrease in protease inhibitor activity in tomato at temperatures below 22°C [11]. At elevated temperatures, the thickness of leaf trichomes normally rises [12].

In alfalfa (*Medicago sativa*), the concentrations of plant secondary metabolites (sapogenins and saponins) were elevated at increased temperatures, suppressing the growth of caterpillar (*Spodoptera exigua*). By contrast, the Green-veined

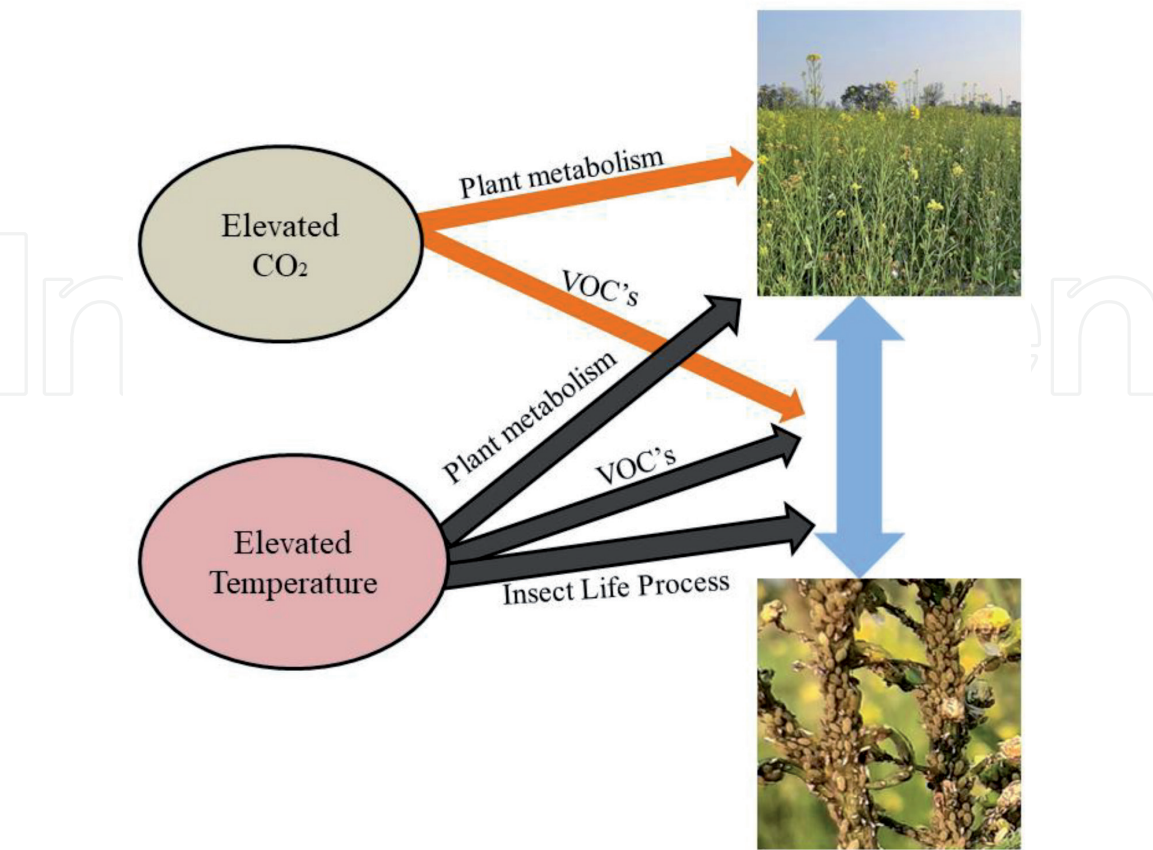


Figure 1.
Effects of elevated CO₂ and temperature on plant, insect and their interaction.

butterfly, *Pieris napi* reacted to warming-mediated poor-quality foliage in Brassicaceae, by consuming significantly higher amounts of plant tissue [13]. However, when fed on oilseed rape plants subjected to different temperatures with nutritional quality variations, the production of aphids (*Myzus persicae* and *Brevicoryne brassicae*) was not affected [14]. Moreover, temperature-induced tobacco shifts (*Nicotiana tabacum*) have an impact on the tobacco hornworm, *Manduca sexta* that the normally accepted law of temperature size, which predicts an improved final mass of ectotherms (e.g. insects) at lower temperature, has been reversed [15].

3.2 Effect of carbon dioxide (CO₂) on insect pest and plants

Higher concentrations of CO₂ with the rise in temperatures in the atmosphere have direct effects on plant metabolism and affect the distribution, abundance and productivity of insects that feed on plants (**Figure 1**). The behaviour of phloem-feeding insects, when supplied with plants grown under increased CO₂, increases compared to leaf chewing insects [16]. When leaf chewing insects like grasshoppers and caterpillar larvae feed on plants that are grown under higher CO₂ levels, more leaf area is eaten than they actually eat [17]. *Spodoptera litura* has been reported to grow under higher levels of CO₂ as a serious pest [18]. The larvae of *Helicoverpa*, grown under high CO₂ ate much more leaf tissue than those under ambient CO₂. However, under elevated CO₂, adult moths increased and lived longer and laid considerably few eggs [19].

The change in CO₂ concentration also influences the plant biochemistry, along with the synthesis of secondary metabolites [20]. The higher concentration of CO₂ is subjected to increased ratio of carbon to nitrogen in plants. Insects are allowed to consume more in order to achieve sufficient dietary nitrogen, resulting in slower larval growth and increased mortality. Phytophagous insects can become more susceptible to changes in atmospheric CO₂ concentration by CO₂ cascading effects on plant biochemistry, as certain plant feeding insect species produce their pheromone molecules on the basis of compounds taken from the host plants [21]. Example: Bark beetles use the mevalonate pathway to generate pheromones, where certain components of aggregation pheromones originate from the hydroxylation of secondary metabolites derived from tree [22]. Besides affecting the plant biochemistry, along with the synthesis of secondary metabolites changes in CO₂ concentration could also affect the plant yield. Example: [23], estimated a yield loss in wheat, maize and cotton of 36 to 40 per cent in a scenario of low CO₂ emissions, and between 63 to 70 percent in a scenario of high CO₂ emissions.

3.3 Effect of precipitation on insect pest and plants

More frequent and extreme precipitation events during climate change are expected to have detrimental effects on the population of insect pests. It is one of the weather factor that acts upon the activities of several insects by means of soil moisture or directly when exposed. Increased summer rainfall encourages a rapid rise in the soil dwelling wireworms, *Agriotes lineatus* population and larvae of root chewing insects, *Agriotes lineatus* [24]. Soil moisture kills insects by means of submerging in water, or affects the soil texture by preventing the emergence of insects. It is also harmful mainly to the insects that are free living in the soil as eggs or as newly-hatched larvae or nymphs.

The effect of the intense raindrops or water in the leaf axils will dislodge or drown small insects such as aphids, or newly-hatched larvae or nymphs from the plants. High proportions of cabbageworm young larvae, *Pieris rapae* and

diamondback moth, *Plutella xylostella* on cabbage, are killed by high precipitation. Intense precipitation also has a catastrophic effect on the boring insect eggs and newly-hatched larvae such as the European corn borer, *Ostrinia nubilalis*, before boring into the plants. It also destroys aestivating adults of the black cutworm larva, *Agrotis ipsilon* and results in drowning of larvae in low-lying areas. Changes in pattern of rainfall are tracked by desert locust, *Schistocerca gregaria* migratory patterns in Sub-Saharan Africa [25]. Precipitation also has a positive association with plant height, total area of the leaves, number of plants and number of leaves, nitrogen and chlorophyll content of the leaves, which has a direct or indirect impact on the population of insect pests.

3.4 Effect of climate change on interaction between insect pests and plants

Climate change can directly affect insect-plant interactions and alter the functioning of both insect pests and plants. The development of secondary metabolites of the plants and other phytochemicals is also affected (**Table 1**). Both plant and herbivore structures can be modified by increasing temperature, CO₂, precipitation, etc. Rise in global temperature, atmospheric CO₂, and the duration of dry season are all likely to have consequences for tropical plant/herbivore interactions, with significant implications on food security and natural habitats. It will increase

GEC driver	Effects	Plant–herbivore	Plant–pollinator
Temperature	+ (Positive)	Flavonoids, condensed tannins, total phenolics, alkaloids, lignin, saponins, volatile terpenes	GLVs, volatile aromatic hydrocarbons, volatile terpenes
	-(Negative)	Condensed tannins, lignin	Volatile aromatic hydrocarbons, volatile terpenes, GLVs, volatile benzenoids, volatile nitrogen containing compounds, nectar sugar concentration
	0 (Neutral)	Cardenolides, lignin, condensed tannins, phenolic glycosides	Volatile terpenes, GLVs, nectar sugar concentration
Carbon dioxide	+ (Positive)	Glucosinolates, alkaloids, flavonoids, saponins	—
	-(Negative)	Phenolics, condensed tannins	Pollen protein
	0 (Neutral)	Saponins	Nectar sucrose concentration
Precipitation	+ (Positive)	Cardenolides, glucosinolates, iridoid glycosides, volatile terpenes, GLV	Volatile terpenes, GLVs, volatile benzenoids, and volatile aliphatics
	-(Negative)	Volatile terpenes, GLVs, volatile aliphatic ketones, volatile nitriles, phenolics, monoterpenes and sesquiterpenes	Volatile terpenes, GLVs, volatile benzenoids
	0 (Neutral)	Lignin, glucosinolates, GLVs, volatile terpenes, polyphenolics, condensed tannins, terpenes	Volatile terpenes, GLVs, volatile benzenoids, volatile nitrogen containing compounds

Table 1.
Effects (+, −, 0) of GEC drivers on plant chemical traits that mediate plant–herbivore and plant–pollinator interactions [26].

the effect of pests benefiting from reduced host defences due to stress resulted from the lack of adaptation to sub-optimal conditions of climate. Climate change could support non-resistant crops or cultivars, contributing to greater insect pest's infestation [27]. But, plants grown under increased temperatures or CO₂ would be less nutritious, as indicated by many researchers and longer larval period and increased mortality of insects is observed upon the insects feeding on them [28]. The defence mechanism of plants against insect pests is diminished by climate change, thereby rendering them susceptible to attack. For example: Early initiation of *H. armigera* infestation in cotton and pulses in Northern India [29]. It has also been found that CO₂ decreases the plant defences towards insect pests. For example, under increased levels of CO₂ in soybeans, the plant defence pathway signalling mediated by jasmonic acid (JA) does not work [30]. Plants become susceptible to insect pests like Japanese beetle, *Popillia japonica* and western corn rootworm, *Diabrotica virgifera* due to reduced production of defensive cysteine proteinase inhibitors (CystPIs). Additionally, the herbivore-induced plant volatiles (HIPVs) are influenced by higher temperatures and CO₂ [31].

3.5 Effect of climate change on plant volatile compounds

The production and release of plant volatile organic compounds (VOCs) can be influenced by changes in abiotic factors and are expected to influence how insects recognise and make use of plant VOCs in intra- and inter-specific interactions [32]. VOCs involved in a number of insect-plant interactions, ranging from positive (e.g., pollination and seed dispersal) to negative (e.g., herbivore defences). The atmosphere could be made more fragrant by global climate, due to release of higher levels of fragrant chemicals in a changing environment by plants. This, in turn, would affect how plants communicate with each other through competitive and allelopathic processes and how they protect themselves from pests, like insects, viruses and pathogens. Few major studies have been conducted to address the effect of changing temperature and gas concentration on VOCs metabolism and expression. Plants are required to develop increased concentrations of VOCs for extended time periods under higher temperatures, thus altering their ecological role in interactions of insects and plants. For example, monoterpene emissions are highly temperature-sensitive exhibiting a 3 fold increase for every 10°C increase in temperature [33]. Therefore, future herbivorous rates are reduced by the development and emission of higher concentrations of VOCs like methyl jasmonate or methyl salicylate that act as plant signalling molecules against insect attack. On the other hand, if a more fragrant atmosphere, confuses pollinators and seed dispersers, beneficial relations may also be interrupted, causing plant reproduction and fitness to be reduced.

VOCs are expected to increase at high CO₂ concentrations because of the positive relationship in between the carbon supply and VOCs production. On the basis of the resource allocation hypothesis, increased CO₂ concentrations are hypothesised to increase emissions of monoterpenes and sesquiterpenes into the atmosphere [34]. As per this theory, when there is an abundance of carbon availability relative to what is required for plant growth, increases the production of C-based plant secondary compounds. In conifers and cultivated plants, the development of certain C-based VOCs increases under high CO₂ conditions [35]. Higher temperature and CO₂ affects the emission of herbivorous mediated plant volatile organic compound (HIPVs) [36]. Any changes made to HIPVs would have a direct impact on the effectiveness of biological control. The olfactory perception of the volatiles will be diminished by change in temperatures, thereby affecting the host position capacity of the natural enemies. Higher CO₂ concentrations would also modify the levels of oxalic and malic acids in chickpea, affecting its herbivorous resistance [37].

3.6 Effect of climate change on plant: Pollinator interactions

For the health of natural habitats, plant-pollinator interactions are important, and most of the human diet is dependent on pollination by insects. By altering the phenology, morphology, and distribution of plants and insects, components of Global Environmental Change (GEC), including higher temperatures, increased CO₂ levels, and modified patterns of precipitation, can directly impact the interactions between plants and pollinators. Another important way where GEC factors can influence plant-pollinator interactions is the modification of phytochemicals (nectar and volatile chemistry) necessary for pollinator attraction (**Table 1**). Floral biogenic volatile organic compounds (BVOCs), that have a major function in attraction of the pollinators and plant-pollinator mutualisms, can be transformed by the components of global climate change. Most of the effects of temperature on floral BVOCs have been shown, with a consistent positive influence on global warming BVOC emissions. BVOCs are actively carried by a protein through the plasma membrane and expelled from the *Petunia hybrida* flowers [38], where the temperature and protein behaviour is always positively associated.

However, anthropogenic airborne pollutants such as ozone and diesel exhaust can destroy floral VOCs once released and increase the foraging times of pollinator. For instance, Farré-Armengol et al. [39] found that appropriate ozone levels in compound-specific ways degraded *Brassica nigra* floral BVOCs, altering the ratio of bouquet compounds that strongly inhibited the attraction of the generalist bumble bee pollinator, *Bombus terrestris*. It is apparent that airborne contaminants have major adverse effects often in unpredictable ways on the pollinator attraction towards flowers (eg. by changing BVOC ratios).

4. Impact of climate change on insects, plants and their interactions

Climate change has significant consequences in every field of agriculture. Climatic changes like temperature, precipitation, humidity and other meteorological components influence the relationship between insect pests and plants. Climate change has enhanced the pest population and their damage potential by increasing the distribution, improving survival rates and developing the adaptability of insect pests. The change in population, mobility, and insect pest behaviour is caused by increasing temperatures, changed precipitation patterns and disrupted gaseous composition of the atmosphere etc. A number of variables that decide how much plants can grow are influenced by climate change. At the same time, incidence of higher temperatures, decline in the supply of water and changes in soil conditions would actually make it harder for plants to flourish. The relationships between plants and insects are altered by increased CO₂ and temperature, with important consequences for food security. Via warming acceleration of plant phenology creates mismatches between plants and insect pollinators. Likewise, changing the development rate of plant in relation to the development of insect can intensify/mitigate the effects of herbivore.

4.1 Impact of climate change on insect pests

The insect pests are seriously affected by overall rise in global average temperatures, weather pattern changes and severe climatic events. With these seasonal and long term changes the population dynamics of many insect pests would be influenced. Different climate patterns primarily affect insect ecosystems and their survival strategies. Significant climate change drivers like higher temperatures

and CO₂ levels and lower soil humidity, have an effect on the nature of population of insect pests and results in subsequent crop losses. Abiotic parameters impose direct effects on the rate of distribution and abundance of insect pest populations by adjusting their growth, survival, reproductivity, dispersal and number of generations per season. Because of the rapid climate change, insect pests are developing increased overwintering stages and number of generations with rapid population growth. Temperature is said to cause direct effects among the abiotic factors. For example, increasing temperatures, from 1.5 to 2.5°C, will surely increase the winter survival and prolong the range of pink bollworm, *Pectinophora gossypiella* [40]. During extended periods of drought, followed by heavy rainfall oriental armyworm, *Mythimna separata*, the populations raises due to the undesirable effects of drought on the activity and abundance of natural enemies of this insect pest [41].

4.2 Impact of climate change on beneficial insects

Climate change impacts the insect pest's natural enemies in a wide variety of ways. Plants grown under higher temperatures and CO₂ and lower precipitation provides various nutritional opportunities for different insect pests, eventually affecting the fitness of insect pest- feeding predators and parasitoids [42]. Despite of a wide variety of host and parasitoid species, variability in precipitation is the key cause for differences in caterpillar parasitism. Parasitism of mealy bug is reduced under conditions of water stress combined with dry conditions in cassava, *Manihot esculenta* [43]. In relation to herbivore hosts and their movement, natural enemies locate their hosts based on their tolerance to environmental extremes. Predatory bugs, *Oechalia schellenbergii* were found to be more effective in destroying the cotton bollworm larvae when pea plants are cultivated at high CO₂ levels [44]. Similarly, in feeding upon the aphid, *Aphis gossypii*, the coccinellid predator, *Leis axyridis*, was found to be more successful at higher CO₂ levels [45].

In hot summers rather than in moderate summers, ladybird beetles (*Coccinella septempunctata*) reduce aphid populations (*Sitobion avenae*) more effectively [46]. Rise in temperature affects the production and release of volatile compounds and extra floral nectar by plants. These secretions help the insects to avoid the attack from natural enemies. Natural enemies need to undergo climate change for breeding purposes, after overcoming temperature extremes; they need to find hosts efficiently through a broad spectrum of temperature and humidity environments. *Trichogramma carverae*, the egg parasitoid fails to recognise hosts at temperature above 35°C [47] and reduces fertility at 30°C [48]. Some parasitoids evolve earlier than hosts in rapid response to temperature and often engage in the extinction of the parasitoid population in absence of the hosts. At elevated temperatures, the rate of insect parasitism will be reduced as host species emerge and move through the susceptible stages quickly before the appearance of parasitoids. Mild winters in temperate regions enhance the survival of parasitoids. Ex: Aphid parasitoids from cereal crops become active during winter and reduce spring aphid populations [49]. The foraging behaviour of ants is often affected by temperature. In general, chemically recruited ants prefer to eat at temperatures lower than those that do not [50]. As a consequence, increased temperature results in pheromone decay changing the trail following action which is disadvantageous to the activity of ant feeding [51]. Hymenopteran parasitoids and small predators sometimes have a negative impact on rising temperatures. Ex: At 40°C BPH is 17 times more tolerant than its natural enemies *Cyrtorhinus lividipennis* and spider, *Pardosa pseudoannulata* [52].

4.3 Impact of climate change on invasive insect species

Climate change is altering important aspects of the environment such as temperature and precipitation, the occurrence of extreme weather events, as well as air composition and land cover. The main factors driving the survival of organisms are temperature, atmospheric CO₂ concentration and available nutrients. It is most likely that changes in these variables might stress the ecosystems and facilitate the chances of invasions. According to the Convention on Biological Diversity (CBD) invasive alien species are considered to be the greatest threat to biodiversity loss worldwide and by altering their geographical structure, function and diversity, inflicts high costs on agriculture, forestry and aquatic ecosystems. Climate change imposes direct effects on insect physiology and their behaviour and indirectly effect through biotic interactions. The introduction, establishment, distribution, impact and changes in the effectiveness of mitigation strategies of invasive insect species are expected to be the significant drivers of anthropogenic and global climate change. Global warming is expected to increase the ecological consequences such as new pests introduction, by changing phenological events such as flowering times mainly in plants of temperate species as many tropical plants can tolerate the phenological changes. The key issue favouring the introduction of insect susceptible cultivars or crops is the invasion of new insect-pests. For example, during 2018 and 2019, fall armyworm, *Spodoptera frugiperda* which is a recent invasive insect from Africa has spread to several countries like India, Thailand, Myanmar, China, Republic of Korea, Japan, Philippines, Indonesia and Australia. The relationship between temperature and the rate of development primarily affects its biology, distribution and abundance. As insect development occurs within a defined temperature range, a change in temperature will consequently affect the developmental rate, life-cycle duration and finally affects the survival. Rise in ambient temperature to near the thermal optimum of insects causes an increase in their metabolism and activity.

From the end of 2019 to early 2020, a desert locust (*Schistocerca gregaria*) outbreak has posed a significant risk to food security and livelihoods across many East African nations. Changes in climate such as increasing temperatures and precipitation over desert areas, and heavy winds combined with tropical cyclones can provide a new environment for reproduction, growth and migration of pest. This means that global warming played a role in establishing the conditions needed for the growth, outbreak and survival of the locust. Oceans absorb around 90 per cent of anthropogenic heat [53] and in the western part of the Indian Ocean in the tropical Ocean system, the most rapid warming occurs with a summer average rise of 1.2°C [54]. In neighbouring areas, this warming has increased the frequency and intensity of extreme climate events and thus favoured the movement of locust plague to various countries like Pakistan, India etc.

4.4 Impact of climate change on plant-pollinators interactions

Climate change is directly linked to the loss of habitat, nutritional deficiencies and lack of various diets, as the abnormal climate affects the growth of plants and flowers. Flowers are forced by climate change to bloom half a day earlier each year, meaning plants are now flowering a month earlier than 45 years ago. Finally, plants that flower earlier mean that they are not pollinated and the bees and butterflies do not have any food left. A study conducted in Spain between 1952 and 2014 found that from the mid-1970s, (*Apis mellifera*) populations appeared early in the spring, as they have adapted quickly to warmer temperatures [55]. Climate change however, has the ability to disrupt the mutualism between plants and pollinators

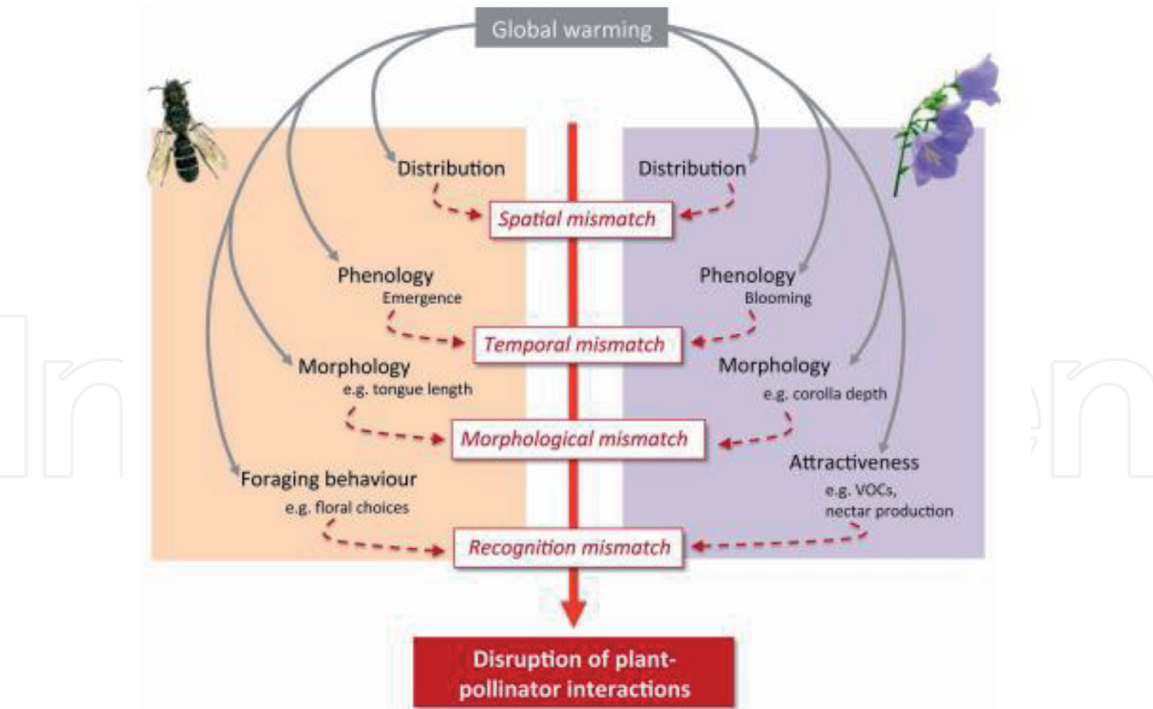


Figure 2.
Potential impacts of global warming on plant-pollinator interactions [56].

and thus lead to potential mismatches, placing plant and pollinator species at risk of extinction (**Figure 2**).

The reduced co-occurrence of interacting partners, the mismatches in plant-pollinator interactions may occur in a shared habitat; this decrease can be temporal or spatial. Increasing attention has been given to such types of temporal mismatches between plants and pollinating insects. A modification of the flowering period of the plant and/or the phenology of the pollinator either of which can be advanced or delayed can drive these mismatches. The co-occurrence of plants and pollinators, needed for interaction to occur, may also be spatially disrupted. The geographical overlap between interacting partners may decrease or increase during global warming, depending on the plasticity, adaptability and life history features of the species in question. In addition to temporal or spatial mismatches, climate change also has the ability to affect the interactions between plant-pollinators that are mediated by physiological or morphological characteristics. The mechanical fit of the interaction can be affected in order to have access to plant resources, in addition to plant morphology, because success of pollination depends on morphological characteristics like length of tongue or overall size of the body. For example, in many species, average rise in temperature has been shown to adversely affect the size of body. In addition, temperature rises will affect the pollinator's foraging behaviour, plant's attractiveness, together with the quality and quantity of plant resources.

4.5 Impact of climate change on plants

Whether it is heat waves, increased flooding or droughts, climate change has many impacts on plants. In addition to these global warming knock-on effects, rising concentrations of carbon dioxide and temperatures has a direct effect on the growth of plant, reproduction and resilience. Rise in local and global temperatures pose a major challenge to the growth and development of plants [57]. The Intergovernmental Panel on Climate Change (IPCC) has suggested that global temperatures would persist to rise by another 1.5°C by 2030 and 2052, if the present

global warming patterns remain the same. Heat stress can damage all plant growth phases from the time of germination to reproduction, resulting in restricted production of important staple food crops [58]. The effect of heat stress on wheat yields, for instance is negative. For every 1°C increase in global mean temperature, a 4–6 per cent decrease in average global wheat yields is expected [59]. Climate change enforces plants to change their dates for leaves and blooming. It is suspected that warmer temperatures potentially destroy tropical forests resulting in more gases causing atmospheric warming and with increase in temperature; cold regions have become increasingly adaptable to growth of plants.

Necessary processes like photosynthesis, respiration, metabolism, and behaviour of stomata are regulated by CO₂. CO₂ concentrations have been rising, from around 350 ppm in 1986 to over 415 ppm in 2019 [60] and are expected to rise to 550 ppm by 2050 as reported by the IPCC. Elevated CO₂ improves the efficacy of photosynthetics, and thereby improves crop growth and yield. Rubisco's improved carboxylation ability that is comparatively poor at present-day CO₂ concentrations in the atmosphere has become the main reason for this improved photosynthesis. However, with increase in CO₂ concentration, at the CO₂ fixation site will raise the CO₂/O₂ ratio, contributing to the effectiveness of Rubisco's carboxylation by reducing the photorespiration rate (**Figure 3**). Under conditions of elevated CO₂, an increase in root to shoot ratio was observed, in this condition plants synthesise a great number of chloroplasts, mesophyll cells, longer stems and extended diameter, length and number of large roots, more lateral root development with changes in branching patterns [62].

4.6 Impact of climate change on insect-plant interactions

Insects and plants are affected by climate change and severe weather actions and the direct impact of anthropogenic climate change has been reported on each and every continent, ocean, and in many main taxonomic groups. Plants experience new environmental problems like higher CO₂ and O₃ levels, increased temperature and UV radiation, and changes in rainfall pattern across the seasons as a result of recent activities of human and their influence on global climate. Insects constitute

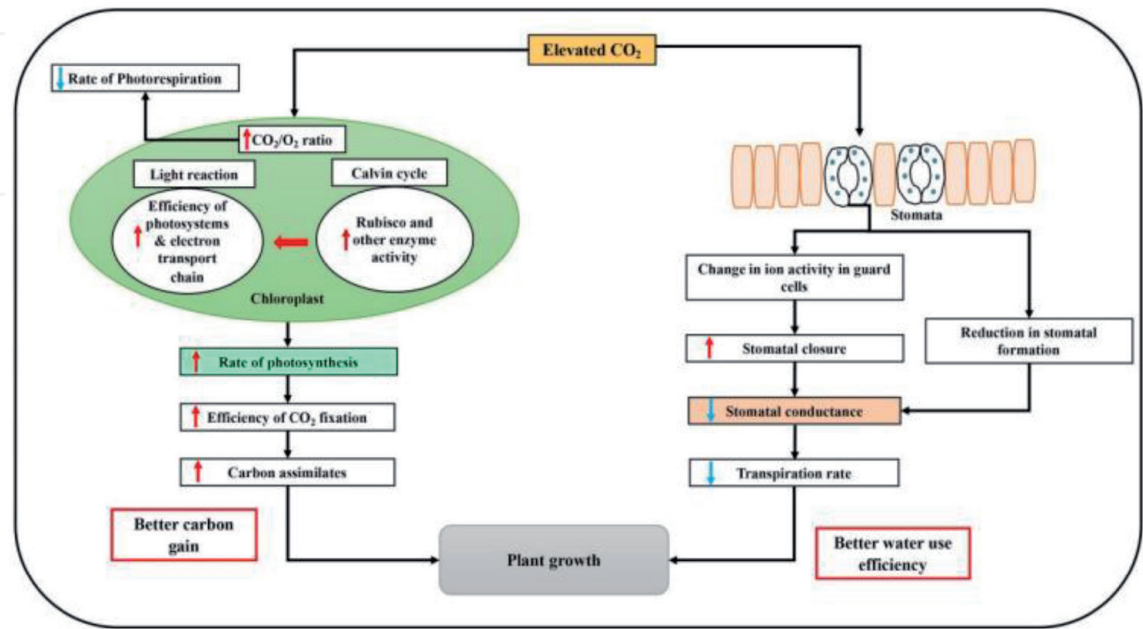


Figure 3.
Effects of CO₂ induced photosynthesis and stomata conductance on plant growth responses [61].

nearly half of the biodiversity and are vital for the structure and function of ecosystem. Because of their close relationship with host plants, through the changes undergone by their host plants, herbivorous insects are likely to experience climatic change direct and indirect consequences. In many ways, global climate changes are reported to influence the interactions between insects and plants. They could directly influence insects, through changes in parameters of physiology, behavioural and life history, as well as indirectly, by means of change in their morphology, biochemistry, physiology and patterns of richness, diversity and abundance experienced by host plants [63]. By functioning as herbivores, pollinators, predators and parasitoids, insects play major roles in ecosystem services and by altering their abundance and diversity, have attained the capacity to modify the services they offer [64]. Over past 20 years, the studies documenting the impacts of climate change on insects have risen exponentially.

4.6.1 Increased temperature

In many global change scenarios meant for plants and insect herbivores, the ecological-niche models use revealed a definite spatial mismatch among the monophagous butterfly, *Boloria titania*, and its larval host plant, *Polygonum bistorta* due to each species expressing differential range expansion in response to changes in climate and land use [65]. These findings indicate that, because of species-specific responses to climate change problems, temperature increase and other altered factors by humans have the capacity to disturb the insect-plant interactions at trophic level. Another example of the impacts of rising temperatures on the generation of asynchrony between insects and their food sources is the winter moth, *Operophtera brumata*. The outbreaks of climate-dependent psyllid, *Cardiaspina* sp. and their effects on the *Eucalyptus* dieback across thousands of hectares of Western Sydney's seriously endangered Cumberland Plain Woodlands (CPW) are due to the effect of change in temperatures. Summer heat waves (maximum above 46°C) combined with resource shortages due to defoliation triggered the *Cardiaspina* sp. outbreak in 2013 and in the CPW it became unnoticeable [66]. Conversely, by mid-2015, population levels grew and large parts of the CPW were defoliated again until a heat wave led to extreme decline in populations of psyllid in early 2017 (up to 46°C maximum).

While most of the studies, have concentrated on negative interactions involving insects on the effect of global warming on trophic interactions. [67] have discussed that how climate change can interrupt or even eradicate mutual interactions like pollination and dispersion of seed in between organisms. By means of simulations based on a real network of interactions between 1,419 pollinating insect species with 429 species of plants, they showed that 17 to 50 per cent of all pollinators studied would suffer a decrease in the supply of food with phenological progress of their floral resources by two weeks. For specialist pollinators, this reduction would be even more extreme. Data on the impact of climate change on the synchrony of host-parasitoid interactions are not as widespread as interactions between plant-herbivores and predator-prey [68] but recent studies have proven that parasitoid and host asynchrony affects of climate change can be direct or indirect through changes in host plant.

4.6.2 Enriched atmospheric CO₂

It affects the physiology of plants, with significant implications on plant growth and biochemical composition. Plant chemical composition influences both positive and negative trophic interactions and decomposition, which will then react to

atmospheric CO₂ concentrations [69]. Even though the impacts of increased CO₂ on plants are erratic and not uniform, increased activity of photosynthetic, production and leaf area/biomass are often exhibited by plants grown under high CO₂ conditions. Higher CO₂ levels could change the primary and secondary metabolism of plants as well. The increase in the supply of carbon for tissues of plant and the subsequent C/N ratio changes influence the amount of nitrogen in plant tissues, triggering a “nitrogen dilution effect”. This lower nitrogen concentration, combined with higher C/N ratio with possible influence on the plants secondary metabolism, suggests lower leaf protein concentration and thus reduces the nutritional value of herbivores. Increased CO₂ usually raises the concentration of leaf carbohydrates and reduces the amount of nitrogen (N) in combination with elevated temperatures. Higher CO₂ exposure depresses the jasmonic acid (JA), a plant defence hormone while stimulating salicylic acid (SA) production. This results in increased vulnerability to chewing insects and increased tolerance to pathogens.

In addition to higher CO₂, elevated ozone (O₃) concentrations in the troposphere also affect plants and insects indirectly. In North America and Europe, tropospheric ozone layer is known as main hazardous and well-known pollutant affecting the ecosystems of agriculture and forests. Since the pre-industrial period, O₃ concentrations have increased by almost 40 per cent and are reported to affect directly the plant species and affect herbivorous insects indirectly. O₃ in plants triggers a cascade of adverse physiological effects, disrupting the process of photosynthesis and reducing the carbohydrates supply in the plant [69]. While higher CO₂ concentrations stimulate the productivity and development of plants, O₃ tends to have detrimental impacts on plants, usually leading to reduced growth and lower quality of nutrition in the leaves. This modification in plants quality resulted in the increased rate of herbivory due to overcompensation by insects because of lower nutritional features of tissues. Plants grown under increased O₃ conditions generally display lower photosynthetic rates, reduced leaf area, premature leaf abscission and damaged branch and root growth. Increased O₃ concentrations are expected to have indirect effects on insect and would depend on the extent of change in the condition of host plant (bottom-up factors) or the influence of natural enemies (top-down factors). Elevated O₃ may alter the population of natural enemies by making changes in their diversity, number and prey quality or by changing the behaviour of natural enemies [64].

5. Impact of climate change on the insect pest management strategies

Dramatic changes in the geographical distribution and population development of insect pests, interactions between insect-host plants, the behaviour and abundance of natural enemies, and the efficacy of crop defence technologies may be caused by global warming and climate change. As a consequence of global warming, the distribution and relative abundance of some insect species susceptible to increase in temperatures in the temperate regions may decrease, while insect pests currently confined to the tropical and subtropical regions may migrate to the temperate regions along with a shift in the production areas of their host plants. As a consequence of global warming and climate change, the relative effectiveness of pest control strategies is likely to change. There is an immediate need to evaluate, under varying environmental conditions, the efficiency of different IPM technologies and develop suitable strategies for mitigating the adverse effects of climate change [70].

Although some impacts of climate change may be optimistic, evidence indicates that pest issues are likely to become more volatile and greater in amplitude overall.

However, due to the complex interacting factors of increasing CO₂ levels, shifting climate regimes and altered frequency/intensity of extreme weather events, predicting the impact of climate change on insect pests is not simple [71]. In addition, differences in the thermal preferences of insects and their natural enemies may result in a lack of cooperation between the two and an increased risk of host outbreaks [72]. Changes in the effectiveness of methods of insect pest control as well as changes in policies of land use and crop management are the result of other indirect responses to insect pests, which can also have a higher impact on the pressure of insect pests than the direct effects of climate change alone. A few examples of direct and indirect effects are the following impacts on insect pests if changing climate conditions are studied in isolation:

5.1 Increases in temperature

The severity of damage caused by insect pests may be increased by increases in temperature. In USA, where increasing temperatures leading to greater insect populations in southern regions have brought about higher use of insecticides compared to colder, higher latitude provinces, such growing insect populations and pressures will lead to more frequent insecticide applications. Such upsurges of toxic chemical applications may have serious adverse effects on human and environmental health. Temperature changes can also decrease the efficacy of some insecticides, such as a decrease in the toxicity of lambda-cyhalothrin, bifenthrin and spinosad to *Ostrinia nubilalis* as a result of elevated temperature after exposure [73]. The effectiveness of parasitoids in the control of pest species and the expression of defensive characteristics used by insect pests against their larval parasitoids has been found to affect even with minor variations in thermal conditions [74].

5.2 Altering precipitation

Extreme or insufficient precipitation can have a major impact on crop and pest interactions, as hot and humid conditions favour many species that are highly susceptible to moisture and rainfall. Also, as found during floods in Iowa in 1993, water-stressed crops are more likely to be affected by pests [75]. Changes in precipitation events are compounded by outbreaks of desert locusts, as demonstrated by their incursion of greater than 10 countries in northern and western Africa in 2004 after heavier than usual rainfall, resulting in severe crop injuries and food scarcities. Locust epidemics are only expected to become more common as the frequency and severity of precipitation events are predicted to increase in the future.

5.3 Increasing CO₂ levels

Increased CO₂ levels can directly lead to increased crop harvests, but any increase in yields can be partially or fully offset by losses caused by insects, pathogens and weeds. For example, in North America, cabbage loopers, *Trichoplusia ni* are observed to ingest a higher amount of leaves under higher CO₂ levels, which is believed to be due to the decreased levels of nitrogen observed in cabbage leaves that grown under these conditions [76].

5.4 Extreme weather actions

Extreme weather conditions can unpredictably affect interactions between crops, pests and diseases, likely leading to the failure of some crop protection strategies and subsequent reductions in yields. For example, *Trichogramma*

evanescens populations were so reduced in May 1993 by exceptionally dry and warm weather conditions in Slovakia that no record of active parasitism of European corn borer eggs was reported that year [77]. In hurricanes, intense air streams can also move fungal spores or insects from overwintering sites to places where additional problems can be caused. Winds associated with Hurricane Wilma thus spread citrus canker widely in Florida, killing 170,000 acres of fruit trees grown commercially [78]. Ecosystems affected by extreme climate events are also automatically more fragile and vulnerable to invasions of space by aliens and indigenous organisms.

6. Climate change impact and risk analysis

Changes in species abundance and diversity due to climate alteration will lead to a decrease in the effectiveness of insect pest management systems, so current monitoring methods need to be strengthened and new ones need to be created to recognise possible changes in pest distribution, population ecology, risk assessment, yield loss and impact assessment. Potential enhancements in pest endurance strategies require wider and deeper inter-centre collaborations to create new IPM options or to disseminate existing ones to new areas where farmers can find them suitable. Excessive use of synthetic insecticides results from existing sensitivities to environmental contamination, human health threats and the return of pests. Numerous botanically and biologically based products are currently used as eco-friendly products. However, both of these pest management methods are extremely environmentally sensitive. Due to rising temperatures and UV radiation and decreasing relative humidity, many of these control tactics may be ineffective [79]. Appropriate pest management techniques, which will be successful in global warming situations in the future, must therefore be created. The resistance of host plants, natural plant products, bio-pesticides, natural enemies and agricultural practises provide a potentially viable alternative to integrated pest control. But, as a result of global warming, the relative effectiveness of many of those control mechanisms is likely to change. Climate change is greatly influenced by biological regulation, which is considered to be an important and successful aspect of IPM programmes, as the relationship between natural enemies and host pests is affected.

The troubling aspect in the absence of natural enemies is the transfer of insect species to new terrains, as it can lead to outbursts of pests. The biggest challenge in the future is to establish efficient model forecasting that would cover the approaches for their management. It is urgent to establish and incorporate modelling methods for predicting changes in the topographical distribution and population development of insect pests and adapting approaches to minimise crop losses. Weather-based pest management systems are valuable decision-making tools that help farmers recognise the risk of outbreaks of pests under different climatic conditions. For alert systems, weather, plant-insect relationship information is very important to take appropriate action to avoid outbreaks of pests and to avoid economic losses. For sustainable agriculture and the mitigation of the effects of climate change on agriculture, assessing the impacts of climate change on crop yield and climate-smart crop growth is significant.

7. Conclusion

In modern era climate change is globally acknowledged fact. It has a serious effect on the diversity, distribution, occurrence, reproduction, development, growth, voltinism and phenology of insect pests and plant species. It also affects


the activity of plant defence and resistance system, invasive insect species, natural enemies, pollinators and insect pest management strategies. Food protection in the 21st century will be the greatest challenge for humanity in the years to come, considering the declining efficiency of production due to the depletion of the natural resource base, the drastic effects of climate change on the diversity and abundance of insect pests, and the scale of crop losses. Coping with climate change is very tedious, due to its uncertainty, ambiguity, unpredictability and differential effects over time and place. It is important and challenging in agriculture to understand abiotic stress reactions in plants, insect pests, invasive insect species, natural enemies and pollinators. The effects of climate change on crop production, mediated by changes in populations of extreme insect pests, should be carefully considered in the planning and implementation of adaptation and mitigation strategies for future pest management programmes. It is then vital to look at the possible impacts of climate change on crop safety in a concerted manner and to establish effective actions to mitigate the impacts of climate change on food security.

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